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(54) **INTRINSICALLY-CALIBRATED**  
**TRIBOMETER**

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CPC ..... **G01N 19/02** (2013.01); **B60T 2210/12** (2013.01); **B60T 2210/13** (2013.01)

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See application file for complete search history.

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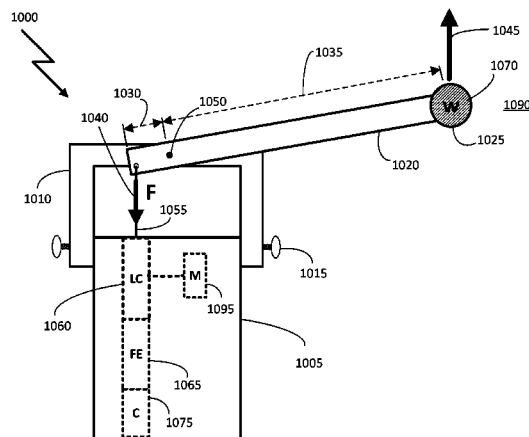
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(57)

**ABSTRACT**

Intrinsically calibrated friction mensuration device has a drive unit with controllable motive member, configured to receive a controllable propulsion force, and to apply tractive force by a Class 1 lever to a weighted test piece. A force engine couples to the motive member, and applies the controllable propulsion force. The device includes a controller imposing a propulsion control signal actuating the force engine to produce the propulsion force. A force sensor joins drive unit and test piece, producing a force signal responsive to a sensed force between drive unit and test piece. The sensed force includes hydroplaning SCOF and hydroplaning DCOF. A method includes applying an increasing tractive force to a test piece at rest; measuring the tractive force; identifying the maximum tractive force applied at incipient motion; identifying the transition between the resting test piece and incipient motion; determining the hydroplaning SCOF; continuing motion; and determining the hydroplaning DCOF.

**20 Claims, 9 Drawing Sheets**



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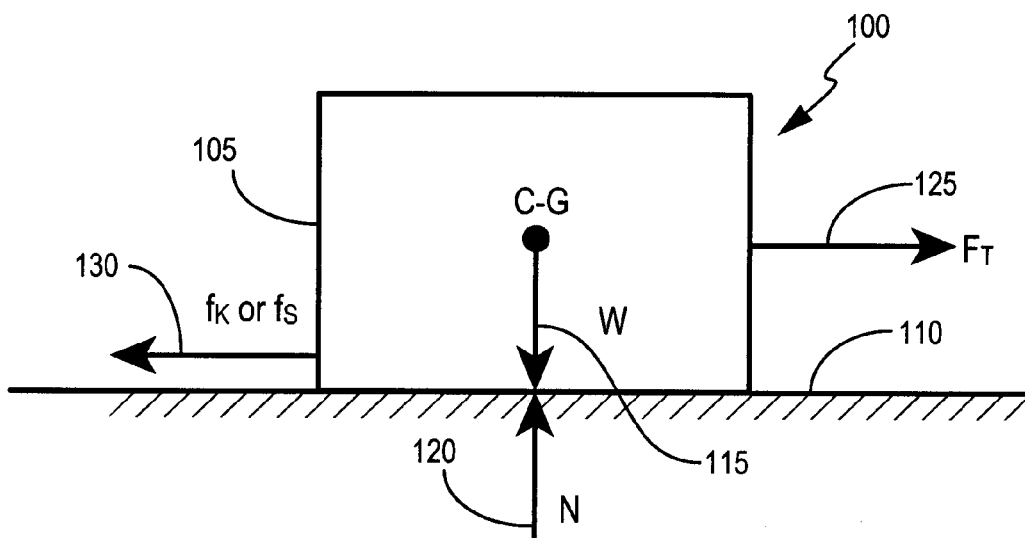


FIG. 1A

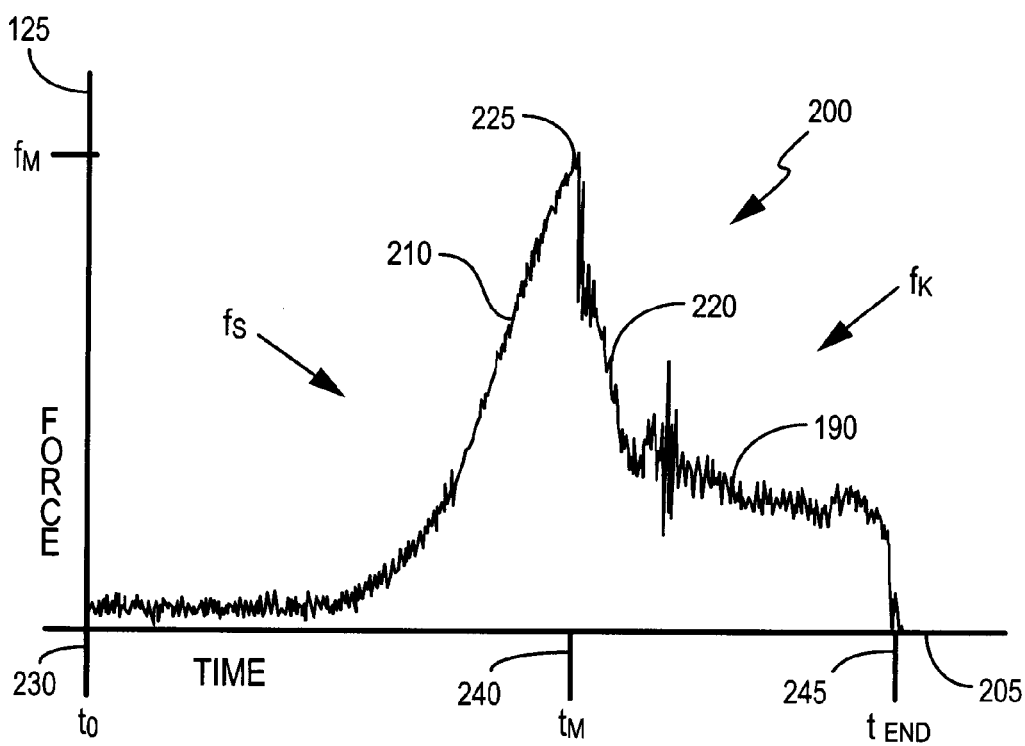


FIG. 1B

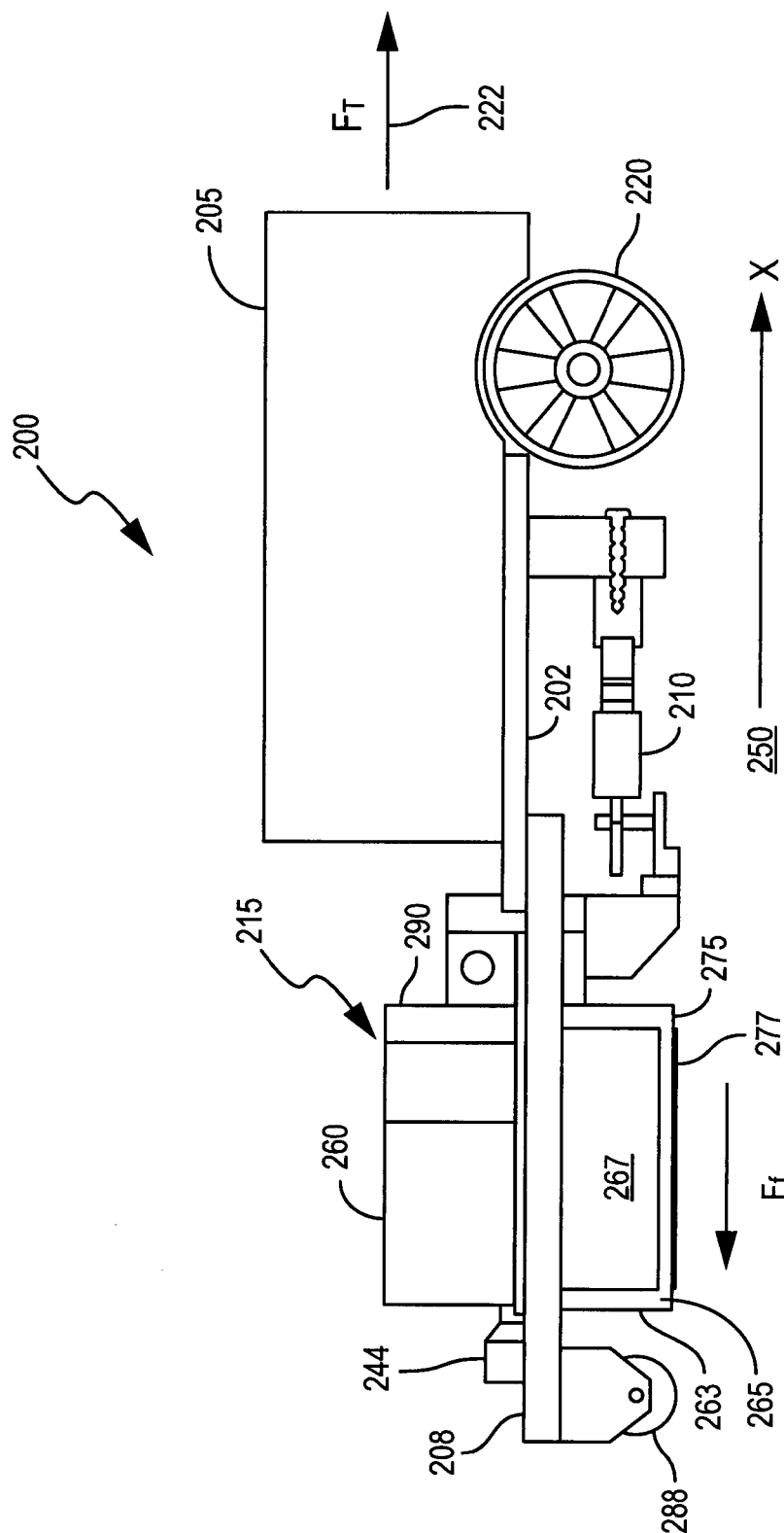


FIG. 2

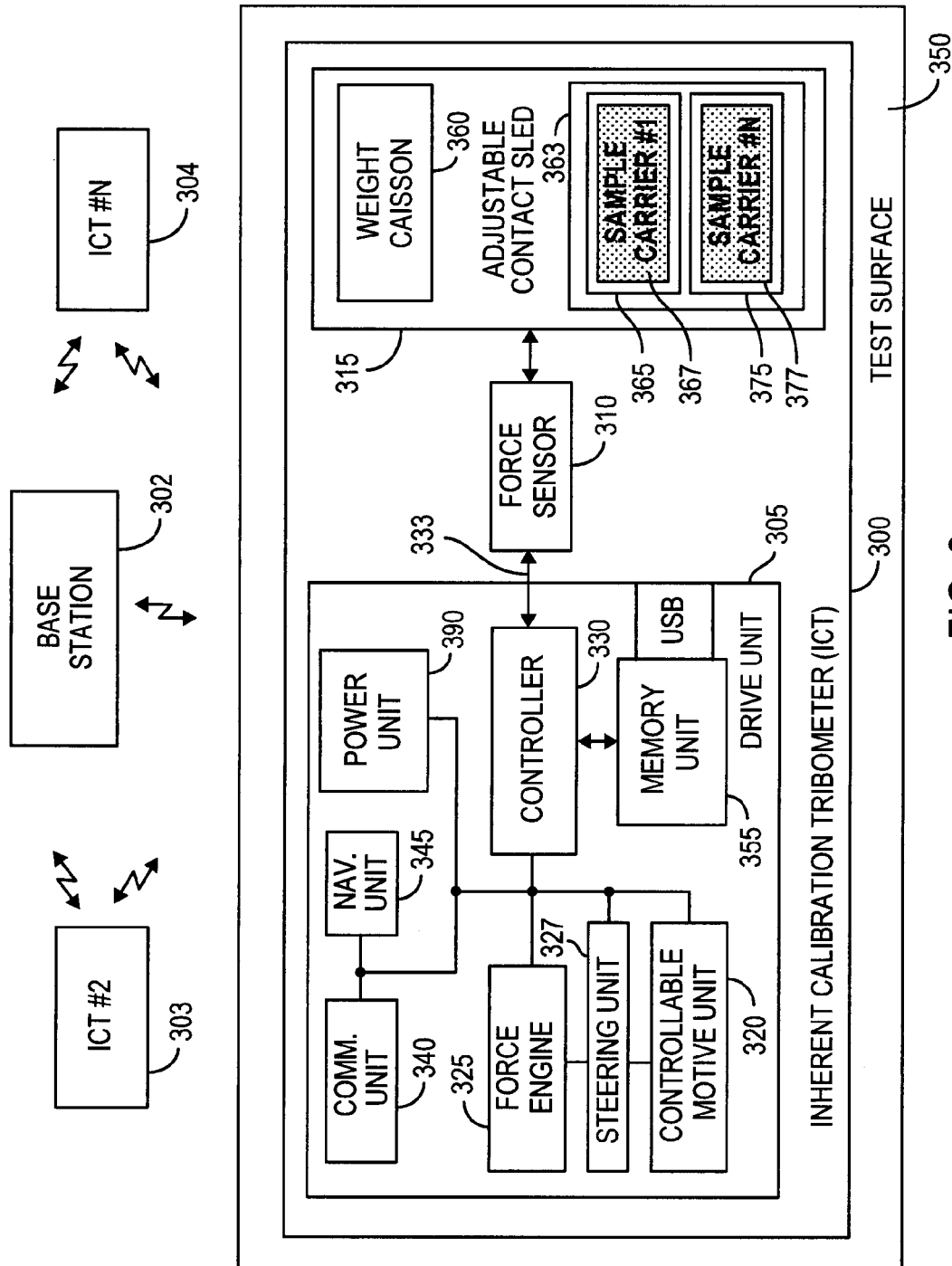
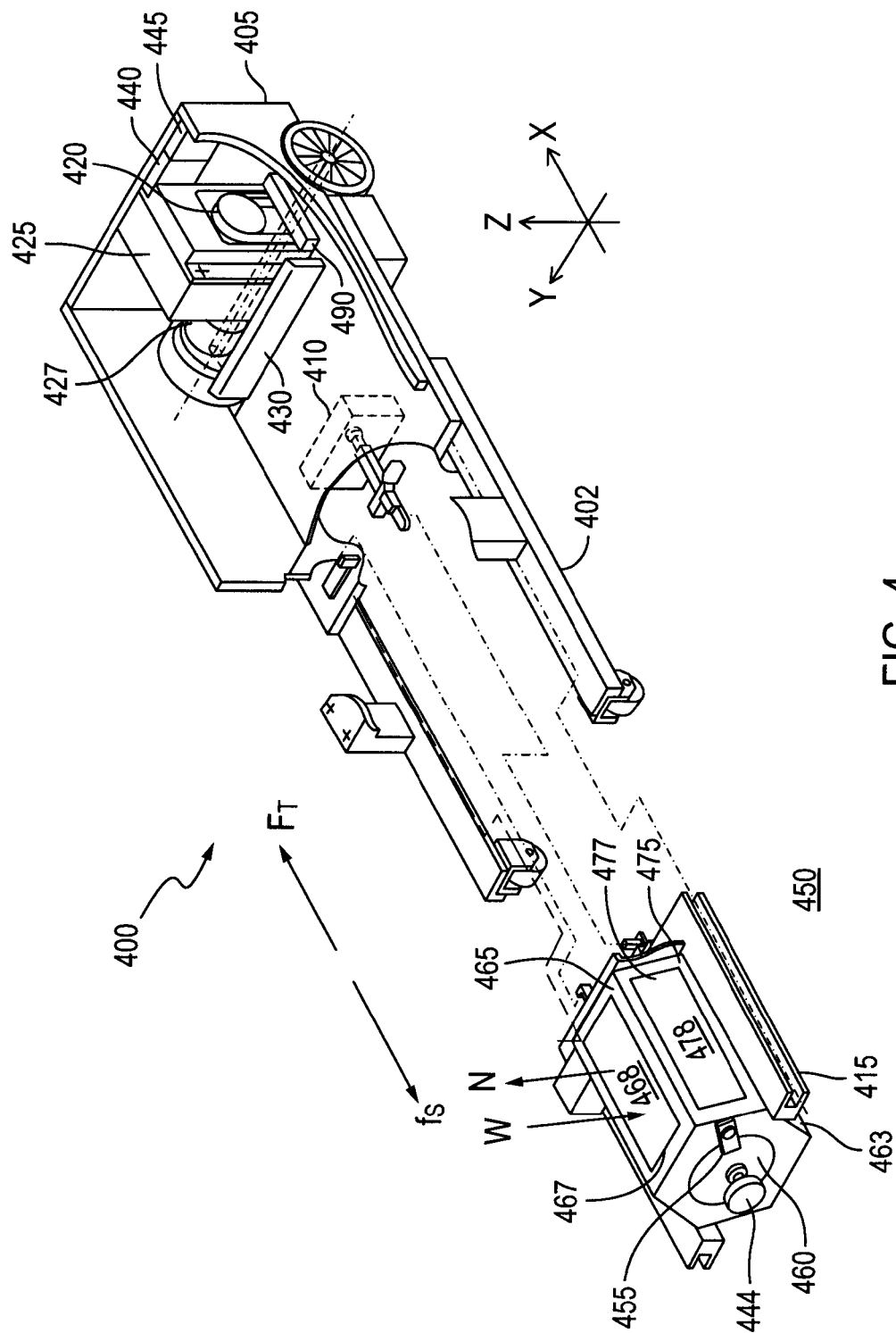


FIG. 3



**FIG. 4**

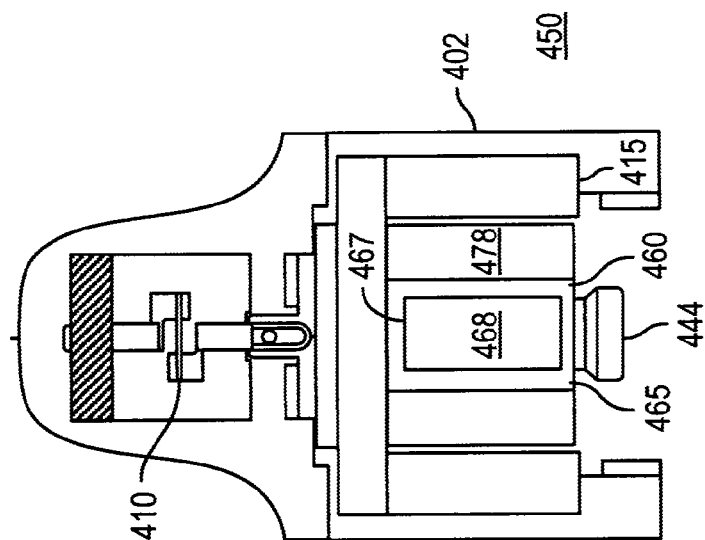


FIG. 6

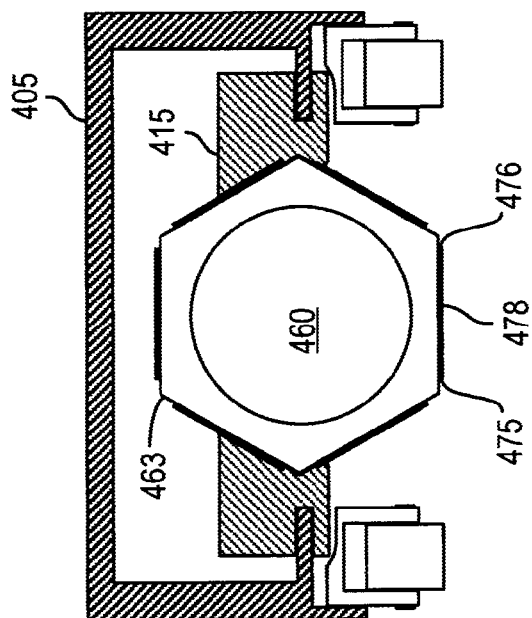


FIG. 5

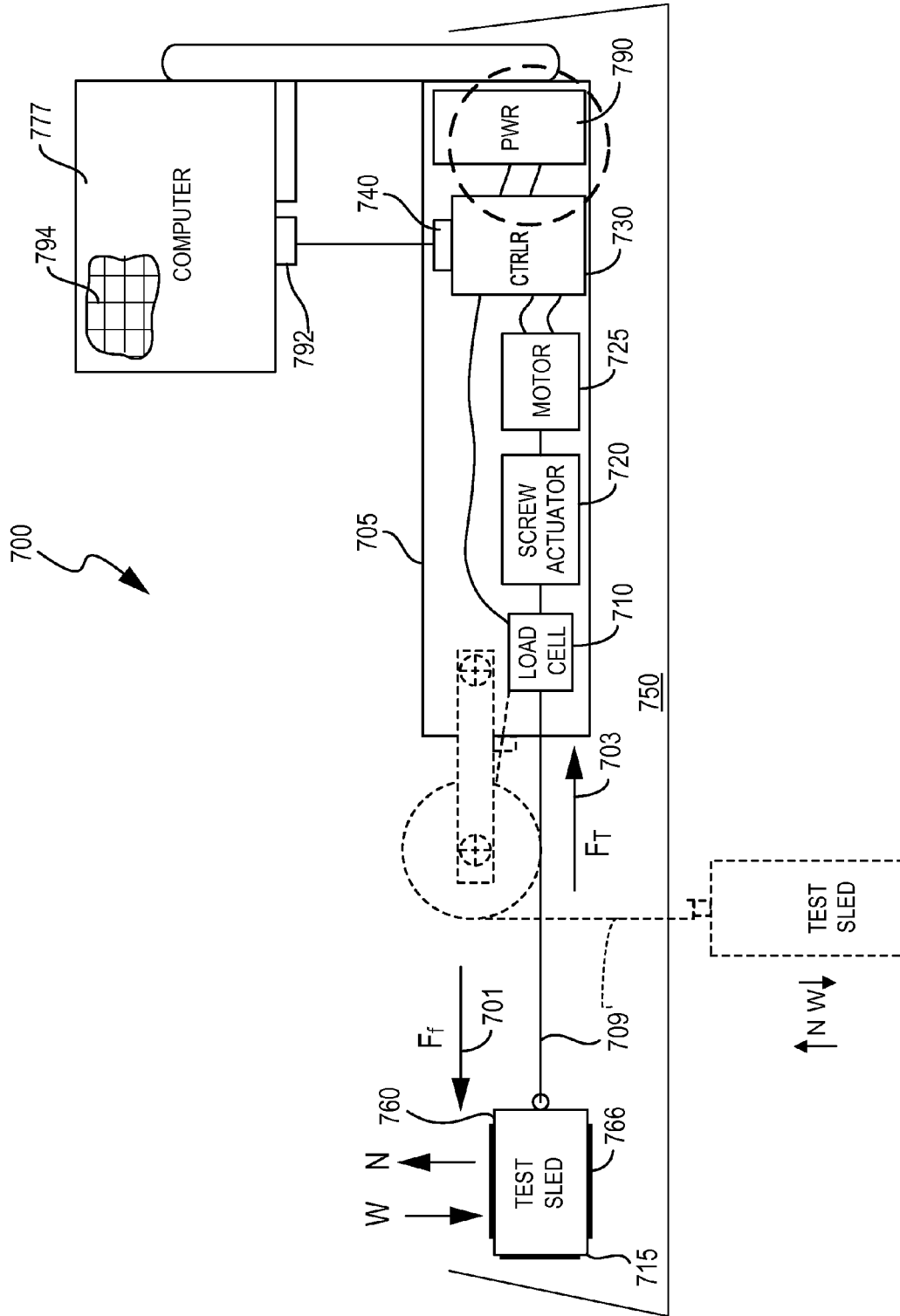
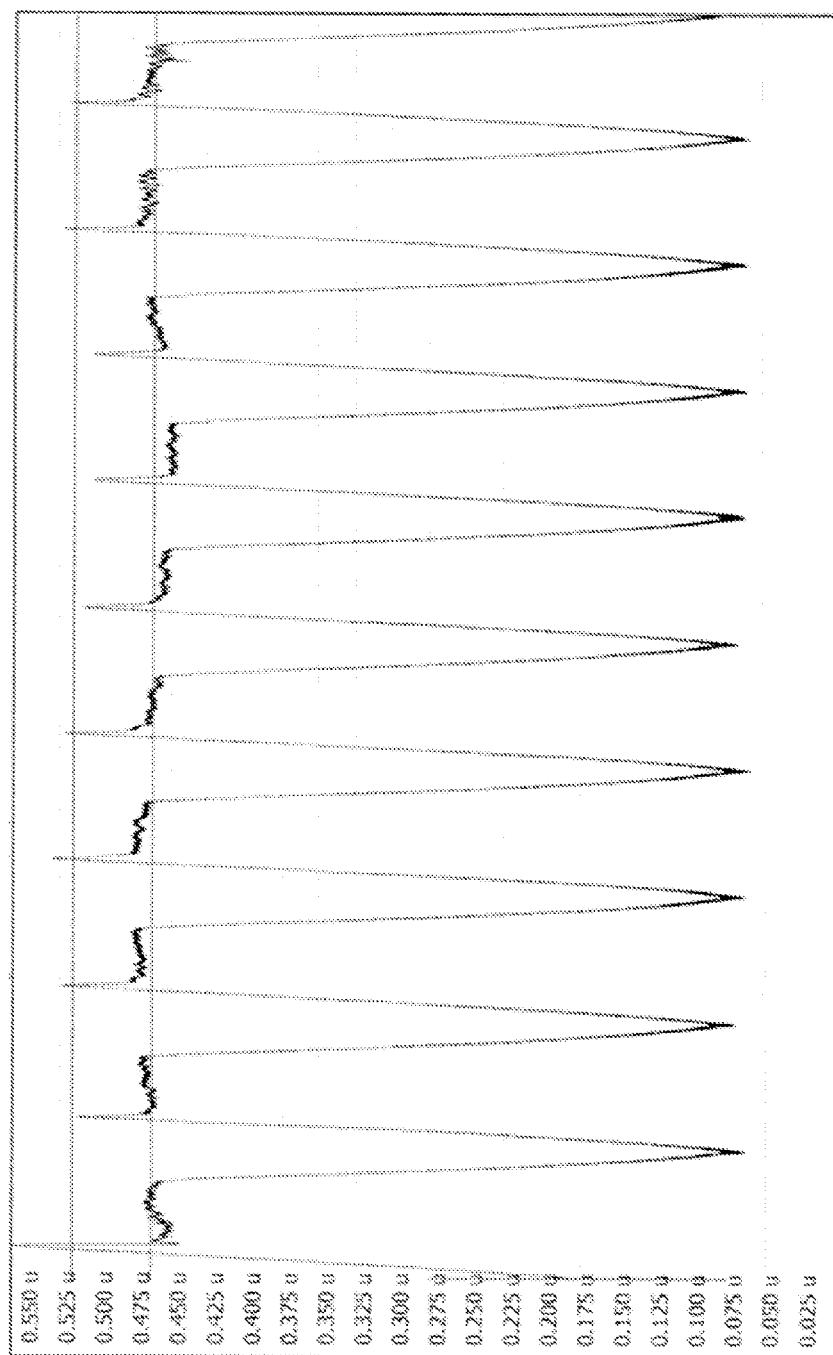


FIG. 7





**MEAN STATIC FRICTION: 0.513**

**MEAN DYNAMIC FRICTION: 0.460**

**FIG. 8**

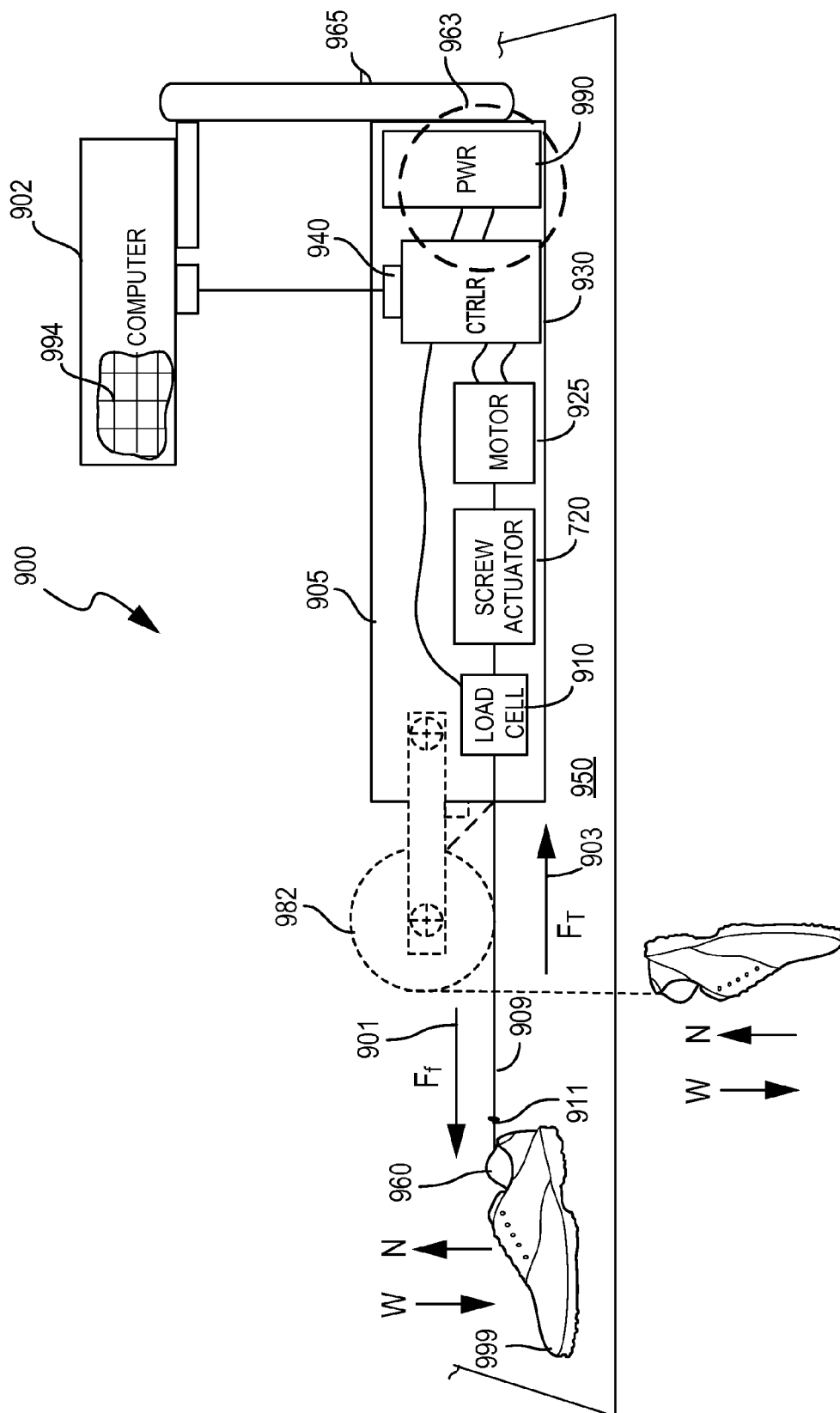


FIG. 9

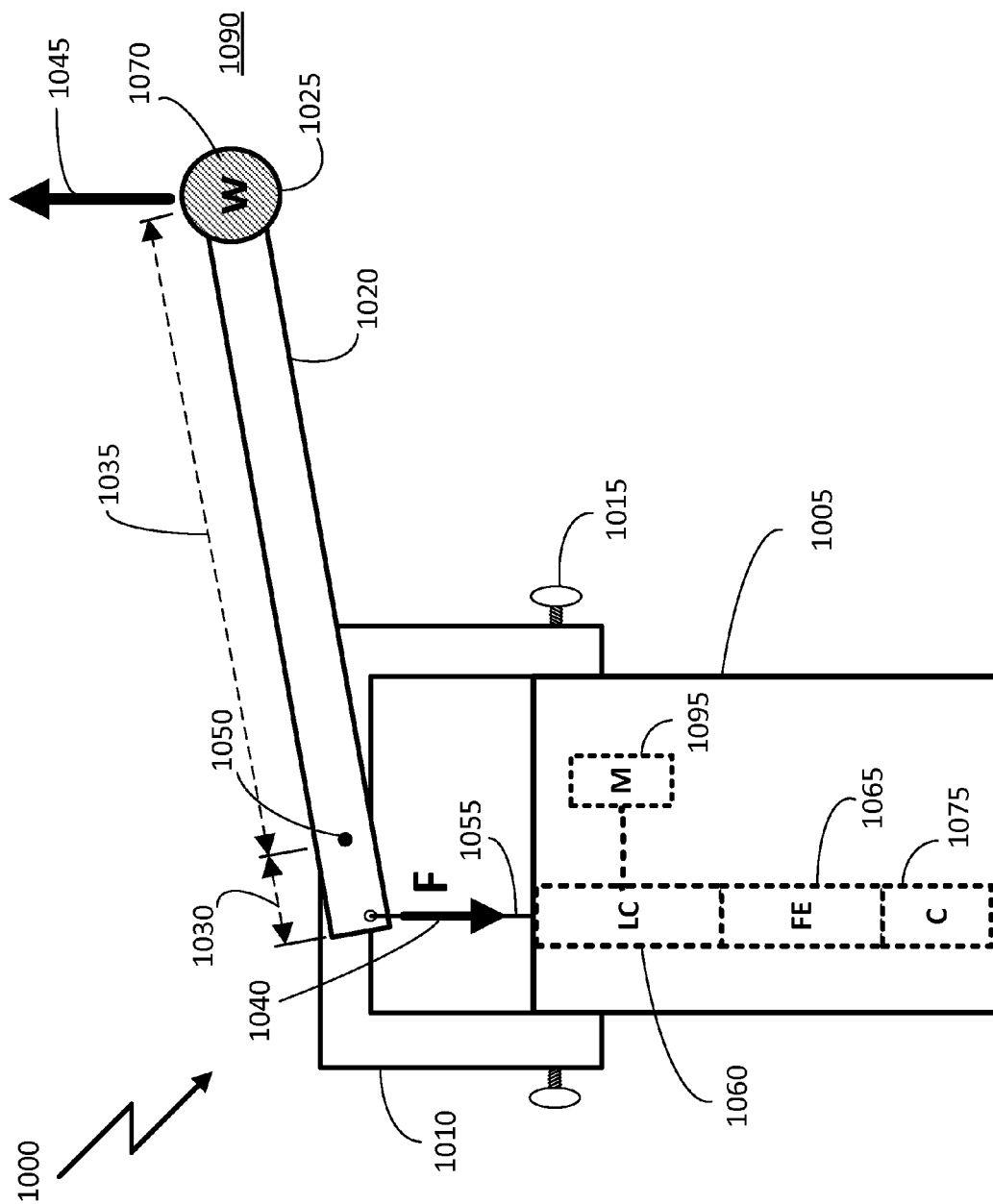


FIG. 10

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# INTRINSICALLY-CALIBRATED TRIBOMETER

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a Continuation-in-Part to U.S. application Ser. No. 14/007,487, entitled "INTRINSICALLY-CALIBRATED TRIBOMETER," filed on 25 Sep. 2013, which is a national stage application of PCT US12/29975, entitled "INTRINSICALLY-CALIBRATED TRIBOMETER," filed on 21 Mar. 2012, which relies for priority upon U.S. application Ser. No. 13/072,626, now U.S. Pat. No. 8,695,398, entitled "INTRINSICALLY-CALIBRATED TRIBOMETER," filed 25 Mar. 2011, which applications and patent are incorporated by reference herein in their entireties.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates generally to the field of test measurement and more particularly to friction mensuration devices and most particularly to tribometers.

### 2. Background Art

Over one million people experience slip, trip, or fall accidents each year and approximately 17,000 die from the resultant fall injuries, second only to the number of automobile accident fatalities. These accidents are particularly serious for the elderly, who may suffer a fall injury that severely impairs their mobility, independence, and general health. These accidents can and do occur in a wide range of environments, including construction sites, private residences, playgrounds and recreational facilities, industrial settings, public and private property (e.g., sidewalks, highways/roadways, streets, parking lots, markets); public transportation facilities (airports, subways, train & bus stations) and facilities for the elderly and disabled. Hence, a great deal of attention is placed on the quality of walkway surfaces used for ambulation by pedestrians.

The criteria for walkway surface safety are determined by consensus of a panel of safety experts, based on measurements of the coefficient of static friction (SCOF) of surfaces under scrutiny. In general, physicists define the SCOF as the ratio of the maximum tangential force needed to cause a standard surface to slip divided by the force holding the surfaces in contact, herein called the normal force. A value of 0.5 for SCOF has been adopted as a threshold of safety for a walkway surface.

It is believed that the most representative measurements of a surface are taken in the field, that is, at the location of the surface to be tested. A large number of friction-measuring field devices (herein, tribometers) are used to perform friction measurements. Each type of field device employs a different effector mechanism for tribologic mensuration. Examples of tribometers include a variable incidence tribometer (VIT), a variable angle tribometer (VAT), a portable inclinable articulated strut slip tester (PIAST), and a family of articulated strut tribometers known in the art as Brunbager Mk. I slipmeter, Brunbager Mk. II slipmeter, and Brunbager Mk. III slipmeter, named after the device developer. An archetypal impact device is the "James" machine, is a bench mounted device, suitable for the laboratory and not the field. Each of the aforementioned tribometers may be characterized as an "impact"-type device, in which the parameter measured results from an impact between a test surface and a material sample affixed to the particular

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tribometer. Similar devices, such as the Sigler Pendulum or the British Pendulum, employ principles of the Conservation of Energy to measure the kinetic forces corresponding to pendulum motion being arrested by a test material.

Each type of impact device is operator dependent, that is, the criteria for the critical onset of motion during testing cannot be uniquely determined. In addition, the "impact" aspect of these devices implies that a kinetic phenomenon is being used to determine a static phenomenon, namely the static coefficient of friction. Application of the First Law of Thermodynamics to the mechanics of impact devices shows that these devices dissipate some amount of kinetic energy during mensuration, causing wide variability in the measured value of "static" friction. Thus, a measurement reported by an impact-type device is an estimated proxy measurement for the static frictional force and, by extension, for SCOF. Not unsurprisingly, impact tribometers tend to generate non-reproducible, divergent numerical values for the same surface and condition under test. In fact, "impact devices" that rely on gravity, on spring loaded pressure, or on pneumatic pressure are actually energy converters that tend not to reliably produce their theoretically expected horizontal and vertical force components. In addition to the impact-type tribometer, a "pull"-type tribometer also is in use. Two devices exemplary of this type are known to ones of ordinary skill in the art as a horizontal pull slipmeter, and a horizontal dynamometer pull-meter. Each device relies on an operator applying a horizontal force on the slipmeter test device, which is coupled to the test sample. The point of motion initiation being taken as corresponding to the SCOF. Some "slipmeters" are closer in physical characteristics to spring-loaded fishing or laboratory scales. Again, an operator applies a horizontal force and notes the point motion begins. Variations induced by the operator are inevitable. The subjective and objective variability of device operation, unintentional or unavoidable application of non-horizontal force, and vagaries in result interpretation, can lead to a myriad of results for the same test conditions. Moreover, each of the "pull"-type devices use a respective test material (neolite, SBR rubber, neoprene/rubber) that is generally unrepresentative of materials used by an actual pedestrian. A difficulty in reported and published measurements derived from impact and pull devices alike is that the devices produce divergent numerical values for their output. In 2005, testimony at an OSHA hearing revealed there was no test procedure or instrument that accurately correlates to the actual human walking and working condition. Thereafter, ASTM International (formerly, American Society for Testing and Materials) withdrew International Certification for all field measurement protocols for Coefficient of Friction, with no replacements. Hence, there is a need for a tribometer that provides a direct measurement for static friction force, which is operator-independent, and which produces results that are reliable, reproducible, and verifiable. All current impact and friction devices that are meant to eliminate stiction, actually produce stiction, confounding the produced test result.

## SUMMARY

Embodiments herein provide friction mensuration apparatus and methods for friction mensuration. The friction mensuration device includes a drive unit having at least one controllable motive member coupled to the drive unit, configured to receive a controllable propulsion force, and configured to apply tractive force to a test piece on a surface responsive to the controllable propulsion force. The device

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also includes a force engine coupled to the at least one controllable motive member, and configured to apply the controllable propulsion force to the at least one controllable motive member. In addition, the device includes a controller coupled to the force engine, and imposing a propulsion control signal to the force engine, in which the propulsion control signal is actuating the force engine to produce the controllable propulsion force. Furthermore, the device includes a force sensor coupled between the drive unit and the test piece, the force sensor producing a force signal responsive to a sensed force between the drive unit and the test piece. In the device, the drive unit is intrinsically calibrated. In some select embodiments, the drive unit is a self-propelled drive unit coupled to the test piece. In other embodiments the drive unit is a stationary drive unit coupled to the test piece.

An embodiment of the apparatus includes the test piece having a preselected test material thereon, wherein the test piece is oriented to place the preselected test material in contact with a test surface, and wherein the test piece receives the tractive force. The sample carrier translates the tractive force into a test force applied to the preselected material sample, and the test force applied to the preselected material sample is representative of a friction force between the preselected material sample and the surface. The sensed force can be a static friction force, or a dynamic friction force.

In another embodiment, the device, in response to a received force signal, the controller actuates the force engine to produce a controllable propulsion force on the at least one controllable motive member and, responsive thereto, imposes a friction force imposed between the test surface and the preselected sample material. In yet another embodiment, the friction mensuration device further includes a mensuration memory coupled to the controller and having memory storage units. The mensuration memory is configured to receive from the controller a plurality of representations of the sense force, and to retain respective ones of the plurality of representations of the sense force. In still other embodiments, the test piece is a contact sled further including a carrier having facets. Each of the facets includes a sample carrier thereon, with each sample carrier being disposed to releasably retain a respective preselected material sample. The carrier can be disposed to position one of the preselected test materials in contact with the surface.

In other embodiments of the friction mensuration device, the force engine applies the tractive force during a first portion of a test period, corresponding to the static coefficient of friction. In still another embodiment of the device, one of the preselected sample materials is a control sample material. In yet other embodiments, the control sample material is a piece of footwear or is a resin rubber constituent of a preselected rubber soling material. Further, a styrene-butadiene rubber, sanded in one direction, using 2000 grit sanding material may be used.

An embodiment of a method of friction mensuration, includes applying an increasing tractive force to a test piece at rest on a test surface at the beginning of a test period; measuring the tractive force on the test piece at rest on a test surface during the test period; identifying the maximum tractive force applied at incipient motion of the test piece on the test surface during the test period; identifying a sample of the test period signifying the transition between the test piece at rest and incipient motion; determining the static coefficient of friction of the test piece relative to the test surface for the test period; and measuring the tractive force used to continue motion in the test sled for the test period.

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The test session can be created from a plurality of sequential test periods. In a method embodiment of friction mensuration the test piece is stopped between selected test periods in the test session.

In other embodiments of the method above can be included applying tractive force to the test piece during a calibration period; suspending the test piece separated from the test surface during the calibration period; and weighing the suspended test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device. In yet other embodiments, the method further includes continuing the tractive force during the test period; stopping the tractive force at the end of a test period; determining the static coefficient of friction of the test piece relative to the test surface; and determining the dynamic coefficient of friction of the test piece relative to the test surface. The method can be for an intrinsically calibrated device, which method includes applying tractive force to the test piece during a calibration period; suspending the test piece separated from the test surface during the calibration period; and weighing the suspended test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The figures herein provide illustrations of various features and embodiments in which:

FIG. 1A is an illustration of a model of tractive, frictional, gravitational, and normal forces used to effect the embodiments of the present invention;

FIG. 1B is an illustration of static and dynamic forces arising from the model in FIG. 1A;

FIG. 2 is a side view illustration of one embodiment of an self-propelled intrinsically calibrated tribometer, in accordance with the teachings of the present invention;

FIG. 3 is a block diagram model of an embodiment of an intrinsically calibrated tribometer, in accordance with the teachings of the present invention;

FIG. 4 is an exploded perspective view of an embodiment of an intrinsically calibrated tribometer in FIG. 2, in accordance with the teachings of the present invention;

FIG. 5 is a rear view of another embodiment of an intrinsically calibrated tribometer, in accordance with the teachings of the present invention;

FIG. 6 is a top view of the embodiment of an intrinsically calibrated tribometer shown in FIG. 5, in accordance with the teachings of the present invention;

FIG. 7 is a side view illustration of one embodiment of a stationary intrinsically calibrated tribometer, in accordance with the teachings of the present invention;

FIG. 8 is an illustration of a multiple period test output;

FIG. 9 is a side view illustration of another embodiment of a stationary intrinsically calibrated tribometer, in accordance with the teachings of the present invention; and

FIG. 10 is an illustration of an intrinsically-calibrated tribometer configured to measure hydroplaning, in accordance with the teachings of the present invention.

The embodiments of the invention and the various features and advantageous details thereof are explained more fully with reference to the non-limiting embodiments and examples that are described and/or illustrated in the accompanying drawings and detailed in the following description. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale, and features of one

embodiment may be employed with other embodiments as the skilled artisan would recognize, even if not explicitly stated.

#### DETAILED DESCRIPTION OF THE INVENTION

FIGS. 1A and 1B are physical and frictional models, respectively, which illustrate the principles of the embodiments described herein. FIG. 1A depicts a physical model 100 having two elements 105, 110 in frictional contact. In general, model 100 can be illustrated with a surface of first element 105 being disposed second element 110. First element 105 may be a test material. Second element 110 may be a test surface. Second surface 110 is depicted as being substantially horizontal, relative to gravitational force G (115). On a terrestrial surface (e.g., an x, y plane in an x, y, z space), first element 105 experiences normal force N 120 opposing gravitational force G 115. In general, normal force N 120 is produced at a right angle (i.e., 90° to the mutual interface between first element 105 and second element 110, that is, where the opposing surfaces of first element 105 and second element 110 meet. When tangential force F 125, which is depicted as substantially horizontal, is gradually applied to first element 105, relative to second element 110, element 105 tends to remain at rest. Force F 125 is resisted by opposing frictional force f 130. As force F 125 increases to a maximum value, relative motion will occur between first element 105 and second element 110. That is, first element 105 will begin to slide over second element 110. The maximum value of frictional force f 130, at the point of movement, corresponds to a value for the coefficient of static friction (SCOF). Typically, a decreased tangential force F 125 may be used to sustain the relative movement, once the critical value of measured force F is reached.

FIG. 1B illustrates a friction model 200, which can be represented within the context of physical model 100 in FIG. 1A, as measured by tangential force F 125, applied as a function of time t 205. Friction force can be manifest in two forms: (1) static friction,  $f_s$  210 and (2) kinetic friction,  $f_k$  220. In general, the laws of friction are empirical in character and approximate in their predictions. Two basic empirical laws of friction can be expressed as: (1) the static friction is approximately independent of the area of contact over wide limits; and (2) the static frictional force is proportional to the normal force N (e.g., force N 120). Typically, static friction force  $f_s$  210 can be associated with the force F 125 applied to at-rest first element 105 in contact with second element 110. As illustrated in FIG. 1B, the period during which this force F 125 is applied, and frictional force f resists in the form of static friction force  $f_s$  210, extends from the initial application of force F 125 at time  $t_0$  230 to the time at which applied force F 125 coincides with the initiation of motion in first element 105 at time  $t_M$  240. At time sample  $t_M$  240, contact is broken between opposing surfaces of first element 105 and second element 110, allowing first element 105 to move relative to second element 110. In this context, such movement is called "sliding." This point of maximum value establishes the value of  $f_M$  225, whose magnitude defines one of the components for determining the SCOF. Once sliding occurs, a smaller, kinetic, force, generally indicated by  $f_K$  220, is needed to maintain motion of the first element 105 in contact with second element 110. The period during which this force F 125 is applied, and frictional force f resists, in the form of kinetic friction force  $f_K$  220 extends from the initial movement of first element 105 at time  $t_M$  240 until the force F 125

is no longer measured, represented by time  $t_{END}$  245. Often, dynamic forces and surface characteristics can provide greater or lesser resistance, as illustrated by oscillations 190 in  $f_K$  220.

The empirical relationship between the magnitudes of the normal component N 120 and the static frictional force  $f_M$  225 at time  $t_M$  240, may be characterized by:

$$f_M = \mu_s \times N \quad (\text{EQ. 1})$$

where  $f_M$  225 corresponds to the value for static friction force  $f_s$  210 at the moment of motion,  $t_M$  240,  $\mu_s$  corresponds to the coefficient of static friction (SCOF), and N 120 corresponds to the normal force at the mutual interface of elements 105 and 110. As understood by those of ordinary skill in the art, an accurate and reliable measurement of  $f_M$  225 can directly produce a SCOF with similar characteristics, whereas friction measurements derived from dynamic processes may deliver unreliable, irreproducible, and divergent results.

In embodiments of the present invention, force F 125 can be gradually applied in a uniformly or monotonically increasing manner, the transition between  $f_s$  210 and  $f_K$  220 can be readily detected, allowing direct measurement of maximum static force  $f_M$  225. An event during which friction force is measured is hereinafter designated as a "test," although parameters other than friction force may be measured during a test.

For the purposes of the present description, the period of time between the test initiation,  $t_0$  230 and test completion,  $t_{END}$  245, will hereinafter be designated a "test period," or simply, an "period." Embodiments in accordance with the present invention can be configured to perform tests and to collect information, including frictional force data, during one or more test periods. Multiple test periods can constitute a test session.

FIG. 2 illustrates a side view of an embodiment of a self-propelled embodiment of an intrinsically calibrated tribometer generally at 200, which can include functional units described in FIG. 3, with respect to tribometer 300. Tribometer 200 is depicted in an example configuration, to illustrate features of certain self-propelled embodiments described herein. Tribometer 200 can include drive unit 205, contact sled 215, and force sensor 210 coupled between drive unit 205 and contact sled 215. Tribometer may be self propelled by at least one controllable motive member 220 attached to the frame of drive unit 205, and configured to receive a controllable propulsion force  $F_T$  222 from force engine 225 (not shown but typically within a case of drive unit 205). Force  $F_T$  causes tribometer 200 to be propelled in a selected direction (e.g., X direction) on test surface 250. Drive unit 205 may include one or more guide rails 202, which may include one or more followers 208. Followers 208 generally support contact sled 215 and assist rails 202 convey tractive force to sled 215. Guide rails 202 can be configured to slidably support contact sled 215 relative to drive unit 205. Wheels 288 typically do not come into contact with test surface 250 during operation but may be used to easily move tribometer 200 in a manner similar to a wheeled luggage carrier.

Embodiments of tribometer 200, relative to FIG. 1A, are configured to contribute minimally, if at all, to the normal reactive force N, which acts in opposition to the gravitationally-induced weight force W. Contact sled 215 can be disposed with slotted support frame 208, which may slidably engage guide rails 202.

Intrinsically calibrated tribometer 200 can include a weight caisson 260 in contact sled 215. Weights, such as

sand- or lead-filled stockinette material can be disposed in caisson 260. Also caisson may be used in conjunction with stanchion 275 which may be used to receive calibrated weights, e.g., weight 290, to create a preselected sled weight for caisson 260 and, by extension, sled 215. Sled 215 can include a faceted sample carrier 263 between caisson 260 and test surface 250. Each facet 265, 275, of carrier 263 can be configured to retain thereon a respective predetermined test sample 267, 277 for frictional testing with test surface 250. In FIG. 2, test sample 277 is depicted to be in flat, parallel contact with test surface 250. However, in other embodiments, it may be useful to place caisson 260 on end.

Turning to FIG. 3, a block diagram illustrating an embodiment of the present invention is shown. Intrinsically calibrated tribometer 300 can include drive unit 305, force sensor 310 and contact sled 315. Tribometer 300 can be disposed on preselected test surface 350. In certain embodiments, drive unit 305 is provided for self-propulsion of tribometer 300. Self-propulsion can be achieved by coupling drive unit 305 to at least one controllable motive member 320, which can be configured to propel drive unit 305 on test surface 350. For example, controllable motive member 320 may be, without limitation, a wheel, a tread, a ball, a roller, a drum, a coil, or a belt. Controllable motive member 320 also may be an element configured to translate propulsive force into horizontal movement of tribometer 300, including, without limitation, a leg/pedal-type element, a crawler-type element, a peristaltic-type element, or a helical-type element.

Controllable motive member 320 can be integral with drive unit 305, or may be articulated, for example, by way of an axle, a spool, a spindle, a joint, a pendant, or a gearbox. At least one controllable motive member 320 is configured to convert a received propulsive force into motion. It is desirable that at least one controllable motive member 320 be configured to propel drive unit 305, and by extension, intrinsically calibrated tribometer 300, smoothly to minimize irregularities in forces transmitted mechanically through tribometer 300, and to provide substantially uniform propulsion.

Drive unit 305 can include force engine 325 coupled to the at least one controllable motive member 320. Force engine 325 is configured to apply a controllable propulsion force to at least one controllable motive member 320; causing tribometer 300 to be propelled in a selected direction on test surface 302. Force engine 325 may incorporate a steering unit configured to directionally manipulate the at least one controllable motive member 320, causing drive unit 305 to change the direction of propulsion. Force engine 325 may be, without limitation, a rotating electric motor, which may be operated by 12V DC power. An example of such a motor may be a 12 VDC REVERSIBLE GEARED MOTOR, such as Model CRA203 (P/N 30570) from Cramer Co., South Windsor, Conn. USA. Of course, force engine 325 may be another suitable motor such as, without limitation, be a stepper motor, a linear DC motor, a brushed DC motor, a brushless DC motor, a piezoelectric motor, or other 5 VDC to 24 VDC motor configured to produce linear self-propulsion of tribometer 300 from power unit 390, whether directly or in conjunction with mechanical motion translation elements, which may be disposed in one or both of force engine 325 or controllable motive member 320. Force engine 325 may be coupled to force sensor 310 by a screw transmission, to permit movement by infinitesimal, and nearly infinite, measures, allowing for an exceptional degree of precision currently unknown to the tribometer art.

Drive unit 305 also can include controller 330 coupled to force engine 325 and configured to impose control signal 337 on force engine 325. Control signal 337 actuates force engine 325 to produce the controllable propulsion force,  $F$  125 from FIGS. 1-2. Typically, force engine 325 produces the controllable propulsion force  $F$  125 in a gradual, uniformly increasing manner 210, as illustrated in FIG. 2, responsive to control signal 337 from controller 330. Controller 330 captures a high-fidelity value of peak friction force  $f_M$  225 at time  $t_M$  240, that is, when contact sled 315 begins to move, relative to test surface 350. Peak friction force value  $f_M$  225 can be used to determine SCOF (see EQ. 1). A frictional force signal 333 received from force sensor 310 can be sampled, for example, at a rate of about 5 samples per second to about 100 samples per second for a period of time during which peak friction force value  $f_M$  225 occurs. Sample values of frictional force signal 333 can be stored in a memory, such as memory 355.

Controller 330 can be a microprocessor, a microcontroller, or a state machine. An example of a suitable controller 330 includes, without limitation, a low-power, CMOS AT90USB64 8-bit microcontroller manufactured by Atmel Corporation, San Jose, Calif. USA. Controller 330 may be an integrated controller, or may be representative of a distributed cooperative of interoperating control elements disposed in drive unit 305. Controller 330 can perform a "Power On Self-Test" (POST) to verify that elements are disposed in a proper power state (ON/OFF), that tribometer 300 is configured to perform a preselected tribometric test in accordance with a predetermined tribometric process, and that sensing and mensuration elements appear operational. In addition, controller 330 can communicate "INITIATE" and "STANDBY" commands to sensing and mensuration elements to place the elements in a known initial state, and to make ready tribometer 300 for a test procedure. Further, controller 330 can communicate "TEST" commands to sensing and mensuration elements, and may cause data output from controller 330 to be captured by a pre-programmed report template for the ease of the operator.

Memory 355 may be coupled to controller 330, or may be integrated therein. Memory 355 may be used to store command, control, and communication information and code, which may facilitate semi-autonomous operation of tribometer 300. Memory 355 also may be used to collect data from force sensor 310 during one or more testing periods. An example of suitable memory 355 can be 2 GBx8 NAND Flash Memory model MT29F2G08 manufactured by Micron Technology, Inc., Boise, Id., USA. In addition, memory unit 355 also may be representative of one of the ubiquitous removable memory devices (e.g., "stick," "card," "pen drive"), typically using non-volatile FLASH memory technology, on which command, control, and sensed information may be at least temporarily stored. Alternately, memory unit 355 can be configured to transfer stored information to such a removable memory device in the usual course of operations, for example, autonomously, or upon command for such a transfer by base station 302.

Controller 330 can be configured to actuate intrinsically calibrated tribometer 300 to perform one test during a test period  $t_0$  to  $t_M$  (230, 245), or to perform multiple tests during a test session constituting respective test periods. A testing session may contain one or more test periods. Actuation of tribometer 300 may be performed by remote communication with controller 330, for example, from base station 302. Intrinsically calibrated tribometer 300 also can be actuated by controller 330 in response to an applied signal or environmental condition or by a signal from navigation unit 345.

Controller **330** can store values corresponding to preselected test parameters, for example, in a memory within controller **330**, in memory **355**, which is coupled within drive unit **305** to controller **330**, or to a discrete memory device, such as a USB memory “stick” which can be physically coupled to drive unit **305** and electrically coupled to controller **330** by way of communication unit **340**.

Furthermore, controller **330** can be configured with well-known routines to determine for each test period or test session, a maximum measured friction force, a corresponding SCOF for a test period or test session, a corresponding DCOF for an period or a test session, a time, a date, location indicia, an acceleration in one or more dimensions, an ambient temperature, an ambient humidity, a pitch, a yaw, a forward or a lateral acceleration or a characterization of a physical characteristic. Acceleration, pitch, yaw, attitude, and absolute or relative position information (represented as location indicia) may be obtained by controller **330** from navigation unit **345**. Also, controller **330** may be configured to calculate statistical values corresponding to aforementioned data collected from selected testing periods including, without limitation, calculating, an average value of  $f_{\mu}$ , an average value of SCOF, average deviation, standard deviation, probable error, average error, force skewness, or kurtosis, as well as test surface temperature, planarity, tilt, and surface and finish characteristics. Such data and the information that results therefrom can confirm accuracy, reproducibility, and reliability of tribometer **300**-obtained data over multiple tests, and can assist in analyzing the preselected sample material, analyzing the preselected test surface, or both, or in characterizing variability in data which may arise under particular circumstances. Controller **330** also may be configured to record date and time for each test data set, relative or absolute location or elevation, or measurement count.

In some selected embodiments, drive unit **305** can be supplied with a communication unit **340**. Communication unit **340** can be configured with at least one of a wired communication port, a wireless communication port, a memory device port, or a display port. Incoming signals to communication unit **340** may include, without limitation, commands, identifiers, and data. Outbound signals from communication unit **340** may include, without limitation, a force measurement value, a sensed environmental condition value, computed values, tribometer position, velocity, or acceleration, position, energy store level, or mesh unit synchronization.

A wired communication port can be, without limitation, a Universal Serial Bus (USB) port, IEEE 1394 serial bus port, an RS-232 serial bus port, an RS-422 serial bus port, or an unshielded twisted pair (UTP) serial port having an RJ-11 connector. Communication unit **340** may have one or more than one of such communication ports, which can be coupled to controller **330**. The Atmel AT90USB64 8-bit microcontroller incorporates, for example, Universal Serial Bus (USB) On-the-Go functionality to provide bidirectional wired communication between tribometer **300** and a base station **302**. Wireless communication between tribometer **300** and base station **302** may be implemented in tribometer **300**, base station **302**, or both, for example, using an USB adapter (or USB dongle), coupled to, or integrated in communication unit **340**. In one non-limiting alternate example, a DWA-210 Xtreme N® Duo USB Adapter (dongle) available from D-Link Systems, Inc., Fountain Valley, Calif., USA may be used. The DWA-210 wireless dongle provides wireless IEEE 802.11a/b/g/n WLAN capability via a bidirectional USB link. Alternately, and without limitation, a

WPAN wireless link may be used. For example, DBT-120 Wireless BLUETOOTH® 2.0 USB Adapter (dongle), also from D-Link Systems, Inc., may implement IEEE 802.15.2/BLUETOOTH® functionality. Also, a WPAN implementation may use an @ANY2400 IEEE 802.15.4/ZigBee™ USB Dongle, from Adaptable Network Solutions GmbH, Dresden, Del. The well-known IEEE 802.15.4 standards, or the ZigBee™ specifications, may exemplify techniques for supporting a point-to-point bidirectional link, between base **302** and tribometer **300**. However, an IEEE 802.15.4 standard, or the ZigBee™ specifications, also may provide a technique by which to implement a cooperative or mesh network or other distributed, intelligent interaction between or among multiple ones of tribometers **303**, **304**, including tribometer **300**. The aforementioned dongle providers, and their vendors, also make available tutorial matter and software, by which such dongles may be controlled. At least a portion of the software provided for a respective dongle may be programmed into memory unit **355**. In yet another alternative embodiment, communication unit **340** may be communicatively coupled to base station **302** by a wireless transceiver different from a USB connection. For example, communication unit **340** may be configured with an electromagnetic communication transceiver, using electromagnetic radiation in the established RF signal ranges, or in the established infrared signal ranges. Acoustic or ultrasonic communication may be effected by communication unit **340**. One of ordinary skill in the art could substitute other configurations and processors to provide similar functionality, in light of the teachings herein.

Controller **330** also may be coupled to navigation unit **345** disposed in tribometer **300**. Navigation unit **345** may be used to determine a location of tribometer **300**, geospatially, relative to base station **302**, or both. In the present context, “determine” can mean to cause tribometer **300** to be propelled to a preselected location, within a predetermined frame of spatial reference (add XYZ to FIG. 3); to resolve the location of tribometer **300**, within the predetermined frame of spatial reference; or both. Navigation unit **345** can include, for example, an accelerometer, an inertial navigation unit, a global positioning system (GPS) unit, or a combination of an accelerometer and an inertial navigation unit, or an accelerometer and a global positioning system (GPS) unit, an accelerometer and an inertial navigation unit, or an inertial navigation unit and a global positioning system (GPS) unit. An accelerometer may be a 1-axis accelerometer, a 2-axis accelerometer, or a 3-axis accelerometer. By increasing the number of axes along which measurements were taken, an accelerometer in the context of the present invention, navigation unit **345** can provide increasing functionality including sensing one or more of acceleration (translational) data, tilt data, shock data or vibration data. An inertial measurement unit (IMU) may be a 4-degrees-of-freedom (DoF), or a 6-DoF inertial measurement unit. By increasing the degrees of freedom in an inertial navigational unit in the context of the present invention, navigation unit **345** can provide increasing functionality including one or more of sensing acceleration data, vibration data, rotation data, tilt data, shock data, and multiple degrees-of-freedom motion data. Such data may facilitate a pre-test calibration of tribometer **300**, an in-test or a post-test correction of a position, a force, or a friction measurement by tribometer **300**, or in-test correction of propulsion direction. Navigation unit **345**, if disposed in the multiple ones **300**, **303**, or **304**, can facilitate purposeful coordinated mensuration of larger areas, for example, simultaneously. Navigation units may be configured with a cooperative inertial navigation module, or



a GPS navigation module, or a custom navigation module, to facilitate precise placement and movement of one or more of intrinsically calibrated tribometers **300**, **303**, **304**. Navigation may be initiated or controlled by base station **302**, or it may be initiated or controlled locally, for example, on tribometer **300**, and reported to base station **302**.

Non-limiting examples of an accelerometer can be an ADXL-103 accelerometer (1-axis), an ADXL-203 or an ADIS-210003 accelerometer (2-axis), or an ADXL-327 accelerometer (3-axis), each from Analog Devices, Inc., Norwood, Mass. USA. Non-limiting examples of an inertial measurement unit can be an ADIS-16300 (4-DoF) or an ADIS-16360 IMU (6-DOF), with each IMU also being produced by Analog Devices, Inc. A non-limiting example of a GPS unit can be an STA2058 TESEO™ GPS platform IC, manufactured by STMicroelectronics, Geneva, CH, capable of providing an absolute GPS position when requested. Of course, an artisan of ordinary skill could substitute other motion detection elements without departing from the scope of the invention herein.

Contact sled **315** can be coupled to drive unit **305** so that contact sled **315** receives at least a portion of the controllable propulsion force, and is drawn in the direction of drive unit **305**. Contact sled **315** can be configured to have a test sample carrier **360** disposed thereon, which is configured to releasably retain preselected material sample **365**. Preselected material sample **365** can be a material to be tested for slip or wear resistance, slipperiness, or other physical characteristic, when applied frictively to a test surface (not shown). Contact sled **315** can be formed with a predetermined mass which, under gravitational force, will impart to contact sled **315** a predetermined weight. However, some types of friction mensuration may call for contact sled **315** to have a greater mass or weight. To this end, some embodiments of tribometer **300** include weight caisson **360**, which can be a shaped framework or container in which one or more slugs, each having a preselected slug weight, may be disposed in weight caisson to alter, typically increase, the predetermined weight of contact sled **315**. Alternatively, weight caisson **360** may be disposed in drive unit **305**, or in both contact sled **315** and drive unit **305**, in accordance with a balanced weight distribution of tribometer **300**. In general, contact sled **315** orients sample carrier **363** to place preselected test material in carrier **365** in contact with the surface **350**. Contact sled **315** conveys the propulsion force to sample carrier **360** which, in turn, translates the at least a portion of the propulsion force into a test force applied to the preselected material sample **365**. Upon initiation of motion of preselected material sample **365**, relative to test surface (not shown), the test force applied to the preselected material sample is representative of a friction force between the preselected material sample and the test surface. The test force corresponds to  $F$  **125** in FIG. 1, and the friction force corresponds to force  $f_M$  **225**, in FIG. 2.

In selected embodiments of tribometer **300**, contact sled **315** may be disposed with a carrier having facets **365**, **375**, with each facet **365**, **375** being disposed to releasably retain a respective preselected material sample thereon. A multifaceted carrier **363** facilitates seriatim tribometry of multiple material samples. For example, first preselected material sample in carrier facet **365** may be used to determine a first SCOF of a dry, clean preselected test surface and, thereafter, second preselected material sample in carrier facet **375** may be used to determine a second SCOF after the preselected test surface has been wetted, contaminated, or both. In other embodiments of tribometer **300**, contact sled **315**, itself, may be configured with facets. In one non-limiting example,

tribometer **300** may employ a contact sled **315**, having a hexagonally-shaped cross-section and six longitudinally-oriented facet surfaces, with each disposed with a respective sample carrier **365**, **375**. As with other embodiments, each respective sample carrier **365**, **375** can be disposed to releasably retain a respective preselected material sample **367**, **377**.

Force sensor **310** couples drive unit **305** to contact sled **315**. As drive unit **305** is propelled, tension is applied to force sensor **310**, in the course of transmitting the propulsion force to contact sled **315**. Force sensor **310** can be configured to sense a tensional force which may develop between drive unit **305** and contact sled **315**, which tensional force is representative of at least a portion of the propulsion force. Force sensor **310** can be, without limitation, a load cell, or a strain sensor, configured to measure loads of between about 0.05 lbf to about 20 lbf, and typically, between about 0.1 lbf to about 10 lbf. One example of a load cell or strain sensor can be a 20-lb rated thin beam load cell, P/N TBS-20 made by Transducer Techniques, Inc., Temecula, Calif., USA, although other load cells or strain sensors may be used. Force sensor **310** can generate force signal **333**, and impose force signal **333** on controller **330**. In general, force signal **333** can be representative of a horizontal friction force created by an interface between test surface and a test sample in reaction to gravitational forces,  $W$  **115**, a normal force, such as  $N$  **120**, and propulsive force  $F$  **125** in FIG. 1. Typically, force signal **333**, when generated by force sensor **310** and imposed on controller **330**, can cause controller **330** to actuate force engine **325** to controllably apply a motive force to controllable motive unit **335**.

Base station **302** can be communicatively coupled with tribometer **300**, for example, by a wired link, a wireless link, or both. Base station **302** may be used to transmit commands to, and to receive data from tribometer **300**. Base station **302** may be a handheld system or smaller, or it may be a notebook, laptop computer, a desktop computer, or an industrial controller configured to communicate with at least one tribometer. In some in-the-field environments, a ruggedized handheld computer **302** may communicate with tribometer. Base station **302** also may be a notebook, or a laptop, or another computing device capable of bidirectional communication with tribometer **300**, and having an operator interface to enter data, to perceive information, or both. A wired link can be a USB connection, a IEEE Std. 1394 connection, an RS-232 connection, an RS-422 connection, an unshielded twisted pair (UTP) connection, or a Controller-area network (CAN) connection. A wireless link can be a USB On-the-Go™ wireless link, an IEEE Std. 802.11 a/b/g/n link, an IEEE Std. 802.15 link (personal area network), or any other suitable non-interfering ISM-type wireless link. Base station **302** can be used to set a value of at least preselected parameter used to control operation of tribometer **300**, for example, rate of controllable propulsion force application, sampling rate for sensed force values from force sensor **310**, or the number or type of sensed force, speed, temperature, humidity, or other sensed data collected from tribometer **300**.

Base station **302** is used to initiate self-propulsion, for example, by transmitting a "BEGIN TEST" signal to tribometer **300**, or by other well-known signal techniques, using an established communication link, thereby removing idiosyncratic, irreproducible variations in force magnitude and direction, applied by a human test device operator to a test material relative to a test surface. Tribometer **300** is configured to produce results that are both accurate and reproducible from test to comparable test, thereby allowing

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substantially direct measurement of frictional forces between a preselected test material and a preselected test surface, and computation of  $\mu_s$ . Consequently, the reckoning of SCOF, in accordance with the application of the present invention, produces SCOF values grounded in actual values of static friction, and not derived or confounded by kinetic processes. Approximately 10 to about 30 automatic force readings may be taken, stored in memory, and displayed during each test period, although more or fewer samples may be taken.

In alternative embodiments, drive unit 305 is configured to be a stationary base 305, in which navigation unit 345 or steering unit 327 may not be used. Also, controllable motive unit 320 may be configured to draw a cord (not shown), such as by a pulley urged by force engine 325. In some embodiments, the pulley may be eliminated to remove its small, but noticeable effect on calibration. Force sensor 310 also may be configured to sense force delivered to adjustable test sled 315 by controllable motive unit 320, by force engine 325, or by both unit 320 and engine 325. Test sled 315 can be configured as a weighted box with up to four (4) to six (6) facets, or sides, with a facet being configured to receive a predetermined material sample. A predetermined weight, such as 5 lbm can be a weight caisson secured in a closed box of test sled 315 by an epoxy resin adhesive, to prevent weight movement. Thus, alternative embodiments of an intrinsically calibrated tribometer 300 may include those that are configured with a stationary base 305, as well as those which are non-stationary, for example the aforementioned self-propelled drive unit 305. In the alternatives, test sled 315 receives an applied tractive force from which static or dynamic friction forces and corresponding static or dynamic coefficients of friction may be measured. Furthermore, in the alternatives, a weighted shoe may be used in place of adjustable contact sled 315, so that frictional parameters of an actual shoe may be measured. Unlike some prior tribometers, the test piece, e.g. contact sled, test sled, or shoe 315, is not slammed against the test surface, inducing error by creating a vacuum between the test piece and the test surface, and by oscillations which may be introduced into a force measurement, as well as introducing stiction.

Tests, self-calibrations and measurements performed by the embodiments of intrinsically calibrated tribometer 300 can be reproducible and operator independent, unlike the current state of the tribometer art. Moreover, tribometer 300 can be intrinsically calibrated using a known test object 315, which may be, without limitation, a contact sled, a test sled, or another test object such as a shoe. Intrinsic calibration can be performed by providing a pulley over the exit point of the tribometer unit 305. Known test object 315 may be attached to force sensor 310 using a strong, substantially non-elastic cord and force engine 325 may apply tractive force, causing known test object to be free hanging. While hanging, one can press the measurement button to take "friction" measurements. In embodiments of the invention, such measurements can provide a ratio of 1.00 between calibration and "friction" measurement, illustrating the absolute, traceable nature of the intrinsic calibration for both static and dynamic coefficients of friction. Once suspended, measurements of known test object weight 315 may be taken, and used to intrinsically calibrate tribometer 300. The intrinsic calibration is operator-independent. Intrinsic calibration using a test object can lead to reliable, reproducible, and verifiable determination of coefficient of friction for each test period or session. This intrinsic calibration configuration and technique also are not known in the current tribometer art.

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The embodiment of FIG. 4, depicts a cutaway and extended version of self-propelled tribometer 400, including drive unit 405. Tribometer 400 is similar to tribometer 200 and tribometer 300, with like parts having similar reference numbers. Tribometer 400 also is configured to perform operator-independent self-calibration, greatly reducing or eliminating operator-induced error. Contact sled 415 is depicted as having carrier frame 402 configured to support a six-sided faceted sample carrier 463. Each facet 465, 475 has a workpiece carrier 467, 477, which is configured to releasably retain a respective preselected material sample 468, 478. In general, each facet 465, 475 may have a length greater than its width, and each facet 465, 475 can be aligned with a longitudinal (X) axis of frame 402. Sample carrier 463 may include a central protuberance 444, or knob, to facilitate rotation of sample carrier 463 on frame 415. Such rotation brings preselected material sample 468, 478 into contact with preselected test surface 450. Lock 455 may be provided on sample carrier 463 to prevent inadvertent rotation or misalignment of sample 468, 478 with surface 450. Lock 455 may have locking elements on both frame 402 and carrier sled 415, although other configurations are contemplated. Lock 455 also may provide registration of sample carrier position and, by extension, correspondence of a preselected sample material to a particular test data set. In some embodiments, lock 455 is configured to lock a preselected sample material under test to be substantially parallel to test surface 450. In other embodiments, lock 455 may be configured to permit a selectable degree of off-parallel alignment, where such alignment would be useful in selecting from among a range of possible interfacial test areas between the sample under test and the test surface.

Weight caisson 460 is depicted as being disposed, in whole, in contact sled 415 solely to facilitate exposition. Weight caisson 460 may be disposed in part, or in whole, on one or both of drive unit 405 and contact sled 415. Also, weight caisson 460 is illustrated as being a container having lateral elements and a fixed-weight caisson; however, weight caisson 460 also may be configurable to vary the gravitational force holding preselected material sample 468, 478, for example, in sample carrier 467 or 477 in contact with preselected test surface 450.

Power unit 490 can provide power to one or more elements of drive unit 305, for example, force engine 425 and controller 430. Power unit 490 may be a battery, a fuel cell, or other energy source configured to supply the power of tribometer 400. In certain selected embodiments, power unit 490 may receive at least some power through a light-weight wired electrical link, or a wireless link, such as an electromagnetic induction power transfer source.

FIG. 5 depicts a view of tribometer 400, illustrating an end of a hexagonally-arranged faceted sample carrier 463. Weight caisson 460 is depicted amid the hexagonal sample carrier, upon which facets, such as facet 475, are disposed sample carriers, such as carrier 477, which in turn, retains test sample material 478. Typically, test sample material 478 is held in place on surface 450 while a tractive force is provided by drive unit 405.

FIG. 6 illustrates a top view of a contact sled 415 in FIG. 4, which includes carrier frame, and force sensor 410. Again, a hexagonal-faceted version of contact sled 415 is shown, although this configuration is not essential to all embodiments. Weight caisson 460 can be seen as including turning knob 444, which can allow a user to turn sample carrier 463 to a selected test sample, such as sample 468 to be place in

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contact with test surface 450 (of course, sample 468 would be rotated to be disposed at least partly in contact with test surface 450).

FIG. 7 is a side view of a stationary embodiment of intrinsically calibrated tribometer 700, in which base 705 can be configured to remain substantially stationary and to apply tractive force 703 to test sled 715 on test surface 750. A rubber-type base can be applied to the stationary-type of tribometer 700 to prevent movement during testing. Tribometer 700 can be similar to tribometer 300, with similar numbers having like meaning. Base 705 generally can be outfitted and configured to include functional units described in FIG. 3, with respect to intrinsically calibrated tribometer 300, without use of self-propulsive or navigational elements. However, positional instrumentation (e.g., GPS or other GIS sensor) may be used, particularly when tribometer 700 is configured for use with plural tribometers. Nevertheless, the operator-independent intrinsically self-calibrating capabilities, and other aforementioned force and coefficient of friction mensuration features also are included in stationary embodiments. Tribometer 700 may communicate using communications unit 740, as well as by keyboard 792, by display 794, or by both. Tribometer 700 may be coupled to test sled 715 by way of hook 711 and cord 709. Force engine 725 can apply motive force to controllable motive unit 720, which may be a spindle, drum, pulley or other uptake apparatus, and frictional force 701 may be measured by force meter 710, as well as by sensing a state of force engine 725 (e.g., voltage, current, power, or torque).

Test sled 715 includes a multiple carrier test bed 763, which may be configured to hold at least one removable carrier for a test specimen 766, which may be placed in contact with test surface 750. In one embodiment, test specimen 766 can be an SBR rubber sensor. Replaceable, preconditioned SBR rubber sensors may be used to help to provide reproducible results. Contaminated sensors may be removed and replaced with fresh sensors. Test sled 715 may operate similarly to contact sled 415, in that test sled 715 generally may have tractive force,  $F_T$ , 703 applied by, and be dragged towards, base 705. Test specimen 766 can be any type of material about which friction characteristics may be of interest. One such material includes shoe sole material; another may include shoe heel material, although test specimens and test surfaces are not constrained to be shoe materials. Indeed, many surface samples, which may be standardized surface samples, may interchangeably be placed into carrier 715 as a test specimen 766. Typically, tractive force,  $F_T$ , 703 is opposed by static friction,  $f_s$ , or by dynamic friction,  $f_k$ , depending respectively on the kinetic state of the tribometer 700. In general operation, a force 701 resistive to the applied tractive force 703 exists while test sled 715 remains at rest on test surface 750, and can be representative of static friction; on the other hand a force 740 resistive to the applied tractive force exists while test sled 715 is in motion, and can be representative of dynamic friction. Typically, as tractive force 703 is applied to resting test sled 715 on test surface 750, the magnitude of measured static friction 701 increases (similar to the force profile in FIG. 1B), until an inflection point is reached, at which motion occurs in test sled 715. During operation, tractive force may be measured during stationary and moving periods, for example, about 10-20 force measurements, and also may be averaged. Tractive force 703 can be representative of the opposing frictional force. The tractive force can be representative of a measured dynamic coefficient of friction 740, when moving or of a measured static coefficient of friction when tractive force has not yet induced motion in

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test sled 715. Test sled 715 can be weighted to achieve actual weight "W," and force engine (e.g., motor) 725 in body 705 can pull cord 709 coupled to test sled 715, which may be dangled free to tabletop 750. This measurement also detects the Normal force (N). Controller 730 in base 705 can be a computer, which can cause force measurements "F" to be taken on pulled cord 709, such that the ratio "F/W" may be calculated automatically. Computer 777, which may be a small (8 in.) tablet or handheld computer, can be external but coupled to controller 730. Conveniently, this method can produce calibration values as well as test values. Because of a concern about the impact of "stiction" forces, when motion is incipient, a first value of dynamic friction (or last value of static friction) representative of stiction may be discarded. Similarly, a first averaged value may be discarded to eliminate "stiction" from analysis. However, all values may be retained, if so configured. Computer 702 may be configured to present on a display, measured values and other indicia of operation. Such indicia may include, without limitation, time, date, ambient temperature, atmospheric pressure, ambient light levels, or ambient humidity. Force measurements may be proportional to a voltage used by motor 707 used to create a force to pull cord 709.

In this way, device 700 may be configured to measure both static and dynamic friction. Base 705 can be weighted to remain stationary, or, alternatively, it can be configured to clamp or to adhere to a surface proximate to test surface 750. With these principles in mind, test sled 715 can be outfitted with at least one test specimen 766, which is held in contact with test surface 750. The measured force interactions between test surface 750 and test specimen 766, at rest and during movement, can be characterized by measured static friction and measured dynamic friction, respectively. In some embodiments, test sled 715 may be weighted, for example, with a five pound weight, for example, in weight caisson 760, although other weights may be used. In addition, test sled 715 may be configured to be outfitted with different types of test specimen 766, for example, to test different types of specimen, without limitation, a shoe material, a non-skid surface, or an unquantified specimen to be analyzed. Tribometer 700 may be intrinsically calibrated, as described elsewhere.

FIG. 8 is a copy of a test session having ten (10) test periods acquiring 10 force/coefficient of friction samples, respectively. The illustrated values of each period are similar to the values shown in FIG. 1B, and are composed of numerous instantaneous values. However, it is shown that force falls to a minimum between test periods/sampling, indicating that the friction mensuration device is stopped and at rest. As tractive force is applied, the peak value of each test period is indicative of incipient motion in the test piece. Comparable values obtained during each test period can be averaged and be subjected to other statistical analyses. The initial value pertaining to stiction can be eliminated from the averaging. Each test period may be about 0.5 to 0.8 seconds in length, and a typical test session may include about 10 periods, such that a test period 800 may be between about 2.5 sec. to about 8.0 sec., a much shorter time than current testing consumes. Longer or shorter test periods or sessions may be used but, for many instances between about 10 test periods can be sufficient, producing accurate, reliable, and reproducible statistical values. Here, the mean measured static coefficient of friction (SCOF) is about 0.513, and the mean measured dynamic coefficient of friction (DCOF) is about 0.460. Of course, other values may be produced for different testing conditions. Note that the first

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measurement of FIG. 8, representing the physical property of stiction, although measured, is discarded.

Turning to FIG. 9, stationary intrinsically calibrated tribometer 900, which can be similar to tribometers 300 and 700, can include base 905, which may be configured to substitute in place of test sled 915, a test article 999, for example, a shoe or other article of study. In the case of a shoe, base 905 may be attach to the test subject shoe 999 by a simple hook 911 and inelastic cord 909 arrangement. Tractive forces then may be applied by base 905 to the test subject shoe 999, as shoe rests on test surface 950. As before, the transition from at-rest to in-motion signifies the transition from static friction to dynamic friction. Where the circumstances of a fall mishap are being investigated forensically, for example, the configuration of base 905 may permit the static and dynamic friction forces of an actual shoe of a fall mishap victim to be tested against the actual surface upon which the victim slipped and fell. Test article 999 may be weighted, for example, using test weight 960. Force and weight measurements made by computer 902, which may be a tablet or handheld device, may be used to determine static coefficient of friction, dynamic coefficient of friction, or both, of test surface 950, test specimen 999, or both. Controller 930 can operate display 994 to display test indicia and to create a hard-copy (printout) of stored, measured, or calculated data. Controller 930 may be similar to the functional units of FIG. 3, and include flash memory in which to store indicia or data, as well as an USB port to facilitate transfer of data or indicia to, for example, a USB-configured portable memory device. Wireless communication is contemplated in some embodiments. Display 994 may be coupled with a hard-copy printer (e.g., shown in FIG. 8), for example, using a WLAN or WPAN protocol, and may display the actual ramp-up of applied static force, and transition to dynamic force application.

In a prototype device in accordance with the aforementioned principles, eight (8) D-size battery cells 990 may be used by base 905 to provide base weight, to power force engine 925, and to operate computer 930. Other batteries may be used in conjunction with a base weight to achieve comparable results. Instead of a spindle or pulley-type device, force engine (motor) 925 may power a screw rod 920 coupled to force back and forth to achieve the desired controllable force application. The screw rod 920 may have a mechanical auto-stop to prevent over driving. Similarly, force engine 925 can include an electrical, mechanical, or electromechanical stop to prevent over-driving. Also, cord 909 may be threaded through pulley 982 to use controllable motive unit 920 to perform weight measurements. It has been determined that the 8 D-cell batteries may be capable of providing up to one year of intermittent service of device 900, and of providing substantial stabilizing weight to base 905. Other power supplies and stabilizing methods may be used. Base 905 (and base 705 in tribometer 700) may be made of an aluminum block, and may include an offset pair of wheels 963, and a retractable handle 965 to facilitate movement in transit much like a piece of rolling (pull-along) luggage. The retractable handle may be fitted with a removably attachable shelf 967 to permit handy access to a keyboard, and/or a display and, perhaps, a printer. Intrinsically calibrated tribometer 900 can include one or more handles and securable elements (not shown) by which to reversibly convert device 900 into a single physical unit, convenient for transport and storage. In addition, base 905 may have pulley 982, from which test sled 715 or test device (e.g., shoe) 999 may be suspended, for example, without limitation, over the edge of a table or other surface. Weight

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and force calibration also may be determined by lifting the suspended shoe 999 via pulley 982 such that shoe 999 is free from contact with surface 950 and is suspended from pulley 982. Weight readings may be made and recorded, so that calibration can reflect the actual weight of the shoe or other test piece, including the Normal force.

Turning to FIG. 10, an adapted intrinsically calibrated tribometer 1000 is shown from a top view. Tribometer 1000 can be used to measure both Static and Dynamic Coefficient of Friction during hydroplaning. Such would be measured, for example, on wet, smooth surfaces, including for example, marble. What has been observed is that a wet surface, due to polar forces, tends to increase stiction (static friction) on an object. Once the polar forces are overcome, as well as stiction of the surface under test, then hydroplaning may occur. Hydroplaning generally occurs at a water-surface interface. Hydroplaning is a phenomenon that depends both on the weight and on the speed of an object on the wet surface. Typically, hydroplaning occurs on wet surfaces at relatively high speed with decrease contact force. In general, a decreased object contact weight and an increased object speed set the stage for hydroplaning on a wet, smooth surface.

Tribometer 1000 can be like intrinsically calibrated tribometer 300, 700, or 900. Tribometer 1000 can include base 1005, much like base 305, 705 or 905. Tribometer 1000 also can include force brace 1010, which can be attached to base 1005 by a pair of thumbscrews 1015, lever arm 1020, and weighted sensor 1025. The principle used herewith is the Inverse Archimedes Principle of the Lever. Lever arm 1020 can be a Class 1 lever arm, having a predetermined lever arm length and being fabricated from a strong but very light material (aluminum, titanium, etc.). Lever arm 1020 can be attached to force brace 1010 at a predetermined position on lever arm, as to create load arm 1030, with the remainder of lever arm 1020 being effort arm 1035. In one non-limiting example, load arm 1030 can be 1 inch long and effort arm 1035 can be 10 inches long. At the interface between load arm 1030 and effort arm 1035 can be fulcrum 1050. Load arm 1030 can be attached by load wire 1055 to load cell 1060. At the end of the effort arm 1035 can be a sensor 1025 of known weight (w). Typically, the weight (w) of the sensor 1025 is between about 0.25 lbs. to about 0.5 lbs.

Continuing with the example, tribometer 1000 can be calibrated to the weight of known sensor 1025, as described relative to tribometer 300, 700 or 900, in place of shoe 999, or a standard weight. Weighted sensor 1025 may be used to probe the characteristics of test surface 1090. Hydroplaning can relate to the presence of a lubricant such as water, a smooth surface, and a device that probes the surface by increasing speed of the device and decreasing the contact weight of the device. In general, by increasing force on the short end of the lever, force is proportionally decreased on the long end.

A force measurement can be taken using a 10:1 amplification of motion, and a 10:1 decrease in contact weight, in order to determine SCOF and DCOF during hydroplaning, using a known weighted sensor 1025 (w). Then, with a known force F 1040, the  $COF=F/10w$ . Force engine 1065 within base 1005, pulls against load wire 1055 to produce a force, F, 1040, sensed by load cell 1060, which is reduced tenfold by lever arm 1020 to produce Force  $F/10w$  1045, and which increases speed on weighted sensor 1025, demonstrating hydroplaning. Load cell 1060 may take between 5 and 100 samples per second of force F 1040, but takes about 10. As with other intrinsically calibrated tribometers, described above, first-sensed stiction-related measurements

can be discarded, so that COF determinations are not distorted by the stiction phenomenon.

During calibration, weighted sensor **1025** is weighed by tribometer **1000**, similar to the calibration described relative to FIG. 9. Weighted sensor **1025** is connected to the force sensor by a pulley and hung over and left free of the surface on which the tribometer rests. The force value  $F$  value is saved, and is a representation of the Normal weight ( $N$ ). During operation, the measured values are divided by the measured weight of the weighted sensor (i.e.,  $N$ ), producing reproducible SCOF and DCOF measurements. As before, to nullify the impact of “stiction” forces, when motion is incipient, one or more first value(s) of dynamic friction (or one or more last value(s) of static friction) representative of stiction may be discarded. Similarly, the first value may be discarded to eliminate “stiction” measurement from the analysis. The successive remaining values may be averaged to produce the SCOF and DCOF measurements.

With respect to FIGS. 9 and 10, embodiments herein contemplate an intrinsically-calibrated friction mensuration device **1000** having a force engine **1065** configured to apply controllable tractive force **1040** to a weighted test piece **1025** on a test surface **1090**. Mensuration device **1000** includes a controller **1075** coupled to the force engine **1065**, and imposing a traction control signal to the force engine **1065**, the traction control signal actuating the force engine **1065** to produce the controllable tractive force  $F$  **1040**. Additionally, intrinsically-calibrated friction mensuration device **1000** includes force sensor **1060** coupled between the drive unit **1065** and the weighted test piece **1025**, the force sensor **1060** producing a force signal responsive to a sensed force between the force engine **1065** and the weighted test piece **1025**, the force sensor having a load cell **1060** therein. Device **1000** also includes a Class 1 lever arm **1020** coupled between the force sensor **1060** and the weighted test piece **1025**. The Class 1 lever arm **1020** has load arm **1030** coupled between force engine **1065** and fulcrum **1050**, and effort arm **1035** coupled between fulcrum **1050** and weighted test piece **1025**. The ratio of the effort arm length to the load arm length provides a predetermined contact force divider, here 10:1, to the controllable tractive force **1040** applied to the weighted test piece **1025**. In addition, the speed attained by the effort arm is increased 10-fold. The predetermined force divider applied to the controllable tractive force  $F$  **1040** produces a predetermined divided controllable tractive force  $F/10w$  **1045** and when predetermined divided controllable tractive force is applied to weighted test piece **1025** on the test surface **1090**, weighted test piece **1025** experiences a measurable decreased force  $F/10w$  and  $10\times$  increase in speed while hydroplaning on the test surface **1090**. The drive unit **1005** can be calibrated by measuring a directional force  $W$  and a normal force  $N$  with the same load cell **1060**. As a result, force sensor **1060** produces a reproducible measurement of the sensed force. The measurement is absolute, traceable, and operator-independent.

With device **1000**, weighted test piece **1025** has a preselected test material **1070** thereon, and weighted test piece **1025** is oriented to place the preselected test material **1070** in contact with the test surface **1090**. Weighted test piece **1025** receives the predetermined divided controllable tractive force, and weighted test piece **1025** translates the predetermined divided controllable tractive force into a test force **1045** applied to the preselected material sample. The test force applied **1045** to the preselected material sample is representative of a friction force between the preselected material sample **1070** and the test surface **1090**. The friction force is measurably reduced during hydroplaning of

weighted test piece **1025**. In selected embodiments, drive unit **1005** is a stationary drive unit coupled to the weighted test piece **1025**. The sensed force is a static friction force related to hydroplaning. The sensed force also can be a dynamic friction force related to hydroplaning.

In response to a received force signal, controller **1075** actuates force engine **1065** to produce the predetermined divided controllable tractive force on weighted test piece **1025** and, responsive thereto, imposes a friction force imposed between the test surface **1090** and preselected sample material **1070** that transitions into measurable hydroplaning. Mensuration device **1000** can include a mensuration memory **1095** (similar to memory **355** in tribometer **300**) coupled to the controller **1075** and having memory storage units, which can be configured to receive from the controller a plurality of representations of the sensed force. The mensuration memory **1095** can be configured to retain respective ones of the plurality of representations of the sensed force.

In embodiments of intrinsically-calibrated friction mensuration device **1000**, weighted test piece **1025** can be a contact sled which includes a carrier having a facet, wherein the facet includes a sample carrier thereon. The sample carrier can be disposed to releasably retain a respective preselected material sample, and can be disposed to position a preselected test material in contact with the test surface. In embodiments, the force engine **1065** applies the controllable tractive force magnified during a first portion of a test period, corresponding to the static coefficient of friction of hydroplaning. Additionally, the force engine applies the magnified controllable tractive force during a second portion of a test period, corresponding to the dynamic coefficient of friction of hydroplaning.

In some embodiments, the preselected test material comprises one of a Neolite® rubber compound, a styrene butadiene rubber (SBR) compound, or an SBR compound sanded until smooth in one direction with 2000 grit sanding material. By manipulating insulators such as SBR rubber, an electrostatic field may be introduced, which may impair test results. This effect is particularly present under dry conditions. By grounding or other electrostatic charge reduction technique, this deleterious effect may be mitigated. The preselected sample material can be a control sample material, which control sample material may be a resin rubber constituent of a preselected rubber soling or traction material.

In view of the foregoing, methods for friction measurement are provided, one method including applying an increasing tractive force to a test sled at rest at the beginning of a test period or a test session; measuring the tractive force on the test sled at rest on a test surface during a test period or a test session; identifying the maximum tractive force applied at incipient motion of the test sled on the test surface during a test period or a test session; identifying a sample of one or more test periods signifying the transition between the test sled at rest and incipient motion; determining the static coefficient of friction of the test sled relative to the test surface for a test period or a test session; measuring the tractive force used to continue motion in the test sled for a test period or a test session; stopping the tractive force at the end of a test period or a test session; determine the dynamic coefficient of the test sled relative to the test surface for a test period or a test session. The method also may include discarding a measurement corresponding to a stiction measurement. The tractive force may be applied by driving a controllable motive element to coupled to a self-propelled device body; by coupling the self-propelled device body to

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a contact sled against a test surface; by increasing the tractive force until incipient motion of the contact sled occurs; by measuring the tractive force against the contact sled applied at the beginning of incipient motion; by measuring tractive force during contact sled motion during a remainder of a test period; by determining the static coefficient of friction of the contact sled with regard to the test surface; and by determining the dynamic coefficient of friction of the contact sled with regard to the test surface.

Embodiments herein also contemplate a method of intrinsically-calibrated friction mensuration, including applying an increasing predetermined divided controllable tractive force to a weighted test piece at rest on a test surface at the beginning of a test period; measuring the sensed force on the weighted test piece at rest on a test surface during the test period; The method continues by identifying the maximum sensed force applied at incipient motion of the test piece on the test surface during the test period; determining the static coefficient of friction of the test piece relative to the test surface for the test period; measuring the sensed force used to continue motion in the weighted test piece for the test period; and identifying the maximum sensed force applied at incipient motion of hydroplaning.

The method of intrinsically-calibrated friction mensuration may include continuing the tractive force during the test period; stopping the tractive force at the end of the test period; determining sensed forces creating during the test period; determining the static coefficient of friction of the test piece relative to the test surface from at least one of the sensed forces; and determining the dynamic coefficient of friction of the test piece relative to the test surface from at least another one of the sensed forces. A test session is produced from a plurality of sequential test periods, and the weighted test piece is stopped between selected test periods in the test session.

The method of intrinsically-calibrated friction mensuration can further include applying tractive force to the test piece during a calibration session; and weighing the suspended test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

The method of intrinsically-calibrated friction mensuration additionally can include applying tractive force to the weighted test piece during a calibration session; suspending the weighted test piece separated from the test surface during the calibration session; and weighing the suspended weighted test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

The method further includes applying tractive force to the test piece during a calibration session; suspending the test piece separated from the test surface during the calibration session; and weighing the suspended test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

Intrinsic calibration method may include applying tractive force to a test piece during a calibration session; suspending the test piece off of a weight-bearing surface during the calibration session; and weighing the suspended test piece.

The examples used herein are intended merely to facilitate an understanding of ways in which the invention may be practiced and to further enable those of skill in the art to practice the embodiments of the invention. Accordingly, the examples and embodiments herein should not be construed as limiting the scope of the invention, which is defined solely by the appended claims and applicable law. Moreover, it is noted that like reference numerals represent similar parts throughout the several views of the drawings, although not every figure may repeat each and every feature that has

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been shown in another figure in order to not obscure certain features or overwhelm the figure with repetitive indicia. It is understood that the invention is not limited to the specific methodology, devices, apparatuses, materials, applications, etc., described herein, as these may vary. It is also to be understood that the terminology used herein is used for the purpose of describing particular embodiments only, and is not intended to limit the scope of the invention.

The invention claimed is:

1. A friction mensuration device, comprising:

a force engine configured to apply a controllable tractive force to a weighted test piece on a wetted, smooth test surface;

a controller coupled to the force engine, and imposing a traction control signal to the force engine, the traction control signal actuating the force engine to produce the controllable tractive force;

a force sensor coupled between a drive unit and the weighted test piece, the force sensor producing a force signal responsive to a sensed force between the force engine and the weighted test piece, the force sensor having a load cell therein;

a Class 1 lever arm coupled between the force sensor and the weighted test piece, the Class 1 lever arm having a load arm coupled between the force engine and a fulcrum, and an effort arm coupled between the fulcrum and the weighted test piece,

wherein a ratio of the effort arm length to the load arm length provides a predetermined force divider to the controllable tractive force applied to the weighted test piece,

wherein the predetermined force divider applied to the controllable tractive force produces a predetermined divided controllable tractive force,

wherein when predetermined divided controllable tractive force is applied to the weighted test piece on the test surface, a corresponding increase in weighted test piece speed is produced and the weighted test piece experiences a measurable hydroplaning on the test surface, wherein a sensed force measurement representative of stiction is discarded;

wherein the drive unit is calibrated by measuring a directional force and a normal force with the same load cell, and

wherein the force sensor produces a reproducible measurement of the sensed force, and wherein the measurement is absolute, traceable, and operator-independent.

2. The friction mensuration device of claim 1, further comprising:

the weighted test piece having a preselected test material thereon,

wherein the weighted test piece is oriented to place the preselected test material in contact with the test surface, wherein the weighted test piece receives the predetermined divided controllable tractive force,

wherein the weighted test piece translates the predetermined divided controllable tractive force into a test force applied to the preselected material sample,

wherein the test force applied to the preselected material sample is representative of a contact friction force between the preselected material sample and the test surface, and

wherein the contact friction force is measurably reduced during hydroplaning of the weighted test piece on the surface.

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3. The friction mensuration device of claim 1, wherein the preselected test material comprises one of a Neolite® rubber compound, a styrene butadiene rubber (SBR) compound, or an SBR compound sanded until smooth in one direction with 2000 grit sanding material.

4. The friction mensuration device of claim 1, wherein the drive unit is a stationary drive unit coupled to the weighted test piece.

5. The friction mensuration device of claim 1, wherein the sensed force is a static friction force related to hydroplaning.

6. The friction mensuration device of claim 1, wherein the sensed force is a dynamic friction force related to hydroplaning.

7. The friction mensuration device of claim 1, wherein, in response to a received force signal, the controller actuates the force engine to produce the predetermined divided controllable tractive force on test piece and, responsive thereto, imposes a contact friction force between the test surface and a preselected sample material that transitions into measurable hydroplaning on a wetted test surface.

8. The friction mensuration device of claim 1, further comprising:

a mensuration memory coupled to the controller and having memory storage units,

the mensuration memory being configured to receive from the controller a plurality of representations of the sensed force, and

the mensuration memory configured to retain respective ones of the plurality of representations of the sensed force.

9. The friction mensuration device of claim 1, wherein the weighted test piece is a contact sled further comprising:

a carrier having a facet, wherein the facet includes a sample carrier thereon, the sample carrier being disposed to releasably retain a respective preselected material sample, and

wherein the carrier can be disposed to position one of the preselected test materials in contact with the surface.

10. The friction mensuration device of claim 1, further comprising: the force engine applies the controllable tractive force during a first portion of a test period, corresponding to the static coefficient of friction of hydroplaning, or the force engine applies the controllable tractive force during a second portion of a test period, corresponding to the dynamic coefficient of friction of hydroplaning.

11. The friction mensuration device of claim 1, wherein the preselected sample material is a control sample material.

12. The friction mensuration device of claim 11, wherein the control sample material is a resin rubber constituent of a preselected rubber soling material.

13. A method of friction mensuration, comprising:

applying a predetermined divided controllable tractive force to a weighted test piece at rest on a wetter, smooth test surface at the beginning of a test period;  
measuring a sensed force on the weighted test piece at rest on a test surface during the test period;

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identifying a maximum sensed force applied at incipient motion of the test piece on the test surface during the test period;

discarding a sensed force measurement corresponding to stiction;

determining a static coefficient of friction of the test piece relative to the test surface for the test period;

measuring a sensed-force used to continue motion in the weighted test piece for the test period; and

identifying the maximum sensed-force applied at incipient motion of hydroplaning.

14. The method of friction mensuration of claim 13, further comprising:

creating a test session from a plurality of sequential test periods.

15. The method of friction mensuration of claim 13, further comprising:

stopping the test piece between selected test periods in the test session.

16. The method of friction mensuration of claim 13, further comprising:

applying tractive force to the test piece during a calibration session;

suspending the test piece separated from the test surface during the calibration session;

and

weighing the suspended test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

17. The method of friction mensuration of claim 13, further comprising:

continuing the tractive force during the test period;

stopping the tractive force at the end of the test period;

determining sensed forces created during the test period;

determining the static coefficient of friction of the test piece relative to the test surface from at least one of the sensed forces; and

determining a dynamic coefficient of friction of the test piece relative to the test surface from at least another one of the sensed forces.

18. The method of friction mensuration of claim 13, further comprising:

applying tractive force to the weighted test piece during a calibration period;

suspending the weighted test piece separated from the test surface during the calibration period; and

weighing the suspended weighted test piece, wherein the weighing is a constituent of intrinsically calibrating a friction mensuration device.

19. The method of friction mensuration of claim 13, further comprising:

measuring an absolute GPS location of a tribometer performing the friction mensuration.

20. The method of friction mensuration of claim 13, further comprising:

generating a mensuration report including output data being disposed into a preprogrammed report template.

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